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SUIPR Report No. 260

TECHNICAL REPORT ECOM-02041-15

Investigation of Fast Wave Beam/Plasma Interactions

Quarterly Report No. 10

November 1968

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UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

CONTRACT DA-28-043 AMC-02041(E)

INSTITUTE FOR PLASMA RESEARCH

STANFORD UNIVERSITY, STANFORD, CALIFORNIA

Technical Report ECOM-02041-15

INVESTIGATION OF FAST WAVE
BEAM/PLASMA INTERACTIONS

U.S. Army Electronics Command
Fort Monmouth, New Jersey

Report No. 15

CONTRACT DA-28-043 AMC-02041(E)

QUARTERLY REPORT NO. 10.
1 June - 31 August 1968

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November 1968

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Stanford University
Stanford, California

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ABSTRACT

This report describes a program of work in which both electrostatic and electromagnetic wave amplifying mechanisms are under investigation. For the former, studies in the absence of a static magnetic field are directed towards verifying the theory for beam/surface wave amplification. Two distinctly different lines are being followed for interaction in the presence of a static magnetic field: Electrostatic cyclotron harmonic wave interaction is being examined, both theoretically and experimentally, and the potentialities of electromagnetic wave growth in the "whistler" mode are being investigated.

FOREWORD

This contract represents a three-year program of research on "Fast Wave Beam/Plasma Interactions" which is proceeding in the Institute for Plasma Research, Stanford University, under the direction of Prof. F. W. Crawford as Principal Investigator. The work is part of **PROJECT DEFENDER** and was made possible by the support of the Advanced Research Projects Agency under Order No. 695. It is conducted under the technical guidance of the U.S. Army Electronics Command. This is the Tenth Quarterly Report, and covers the period 1 June to 31 August 1968.

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I. INTRODUCTION

The wave amplification effect associated with the interaction of an electron beam and a plasma has attracted considerable attention over the last few years, particularly from microwave tube specialists to whom such interactions offer possibilities of constructing very high gain devices which should be electronically tunable over wide frequency ranges. Since the plasma plays the role of a conventional slow-wave structure, the interaction region should be free of metallic structures, a particularly significant characteristic if millimeter wave operation is envisaged.

The work being carried out under this contract is directed primarily towards utilizing the beam/plasma amplification mechanism in microwave device applications. So far, despite the efforts of many groups, it has not been possible to realize this potential fully. The most serious obstacles to progress are that efficient coupling of an rf signal into and out of the interaction region has been found difficult to achieve, and that the amplifiers are frequently very noisy compared with conventional microwave tubes. The necessity of providing the means of plasma generation within the device, and the presence of a relatively high background gas pressure, add constructional problems beyond those normally encountered with vacuum tubes. Although satisfactory engineering solutions to these latter difficulties could certainly be found, the coupling and noise problems still require considerable further study to determine whether competitive devices can be developed.

Of the many widely differing aspects of beam/plasma interaction, three were originally chosen for close examination under this contract. The first of these is the interaction of an electron beam with a plasma when the modulating fields, and the wave growth, are in either the first axisymmetric mode, or in the first azimuthally-varying mode. Since with transverse modulation several interesting interaction and coupling mechanisms become possible, a thorough investigation of such phenomena is being made under the contract.

Most previous work has been concerned with the theoretical description and demonstration of beam/plasma interaction mechanisms that can be derived from cold plasma theory, i.e., from theory in which it is assumed

that the plasma electrons have no thermal or directed motions, and that the injected beam is monoenergetic. When a dc magnetic field is present, microscopic theory, in which single-particle behavior is followed, predicts a much wider range of amplification mechanisms. Some of these are simply modifications of those occurring in the absence of the magnetic field, while others involve interaction of beams with transverse energy with slow "cyclotron harmonic waves." This constitutes our second area of interest, i.e., that of wave growth in magnetoplasmas when the electron beam has a substantial component of transverse energy.

Our third area of interest is in electromagnetic wave amplification. Theoretical studies predict that, in addition to electrostatic wave growth phenomena such as those just described, there should be appreciable growth in the "whistler" mode when an electron beam with transverse energy interacts with a magnetoplasma. This mode is a right-hand, circularly-polarized electromagnetic wave, i.e., its electric field vector rotates in the right-hand sense, which is also (conventionally) the sense of rotation of the electrons about the magnetic field lines. If a beam with transverse energy is moving along the field lines, there is consequently a possibility of energy being transferred from the electrons to the wave, and hence, for wave amplification to occur. Our work under this contract has shown, however, that over the range of parameters of practical interest, there are competing electrostatic beam/plasma interactions which would preclude observation of small-signal growth in the whistler mode. Attention has consequently been focused in our most recent work on the possibilities of obtaining amplification with alternative electron velocity distributions, e.g., the loss-cone type, and by parametric interaction in a Maxwellian plasma. If significant growth is predicted theoretically, experimental work will be carried out to demonstrate these types of interactions, and to examine their potentiality for coupling to slow- and fast-wave circuits. Here "fast-wave" is interpreted to mean that the phase velocity of the wave is of the order of the velocity of light.

Previous quarterly reports (QR) have described the background for each of the topics in detail. Progress made during the reporting period will be described in the succeeding sections.

II. BEAM/PLASMA AMPLIFICATION

Amplification due to interaction of an electron beam with an unmagnetized plasma has been studied at Stanford and elsewhere. Experimentally, electronic gains as high as 20 dB/cm have been observed in both $m = 0$ and $m = 1$ modes, at frequencies up to 1 GHz, and reasonable agreement has been obtained with theoretical predictions. Although electronic gain has been observed, however, the achievement of net gain between an input and an output is an elusive goal due to the difficulty of achieving efficient coupling between the beam/plasma system and external circuits. One of the principal aims of this study is to investigate coupling methods in the hope of realizing net gain.

When the beam fills, or nearly fills, the plasma region, the rf fields penetrate appreciably into the region external to the plasma. Under these conditions, and provided that the plasma is bounded by a dielectric (with or without an additional external conductor), the interaction is effectively between the space-charge waves of the beam and surface waves propagating on the plasma column. In this case, it should be possible to couple efficiently to circuits external to the plasma. For this reason we are studying a system in which the beam and plasma fill a dielectric tube.

During the past quarter, further computations of the dispersion relation describing beam/plasma wave interaction have been carried out with a view to determining the nature of the instabilities predicted, and the influence of geometrical parameters on the amplification.

(A) Theoretical Studies

Previous QR's have described theory and computations for the $m = 0$ and $m = 1$ surface wave dispersion relations. We are now engaged in the more difficult task of analyzing in detail the interaction between these waves and an electron beam. In an experimental situation, it is not possible to have a uniform beam completely filling the plasma region, due to various effects which cause radial homogeneity, and DC focusing. Consequently, some beam/body wave interaction is always present, i.e., interaction of the type that would occur near ω_p in an unbounded plasma.

It is essential to study this by considering the effect of the beam radius on the interaction. Since the surface waves are strongly influenced by the external conductor surrounding the tube, this effect should also be studied. Now, for the geometry of Fig. 1, the dispersion relation for the $m = 0$ mode can be shown to be,

$$D_0(\omega,k) = \begin{vmatrix} I_0(ka), & -I_0(ka), & -K_0(ka), & 0 & 0 \\ \epsilon_{bp} I_1(ka), & -\epsilon_p I_1(ka), & \epsilon_p K_1(ka), & 0 & 0 \\ 0 & I_0(kb), & K_0(kb), & -I_0(kb), & -K_0(kb) \\ 0 & \epsilon_p I_1(kb), & -\epsilon_p K_1(kb), & -I_1(kb), & K_1(kb) \\ 0 & 0 & 0 & I_0(kc), & K_0(kc) \end{vmatrix} = 0 \ , \tag{1}$$

where,

$$\epsilon_p \equiv 1 - \frac{\omega_p^2}{\omega^2} \quad \text{and} \quad \epsilon_{bp} \equiv 1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_b^2}{(\omega - v_b k)^2} \ , \tag{2}$$

and the various symbols have the meanings ascribed to them in previous QR's.

Solution of Eq. (1) for complex ω and complex k, as is required for a comprehensive stability analysis,[1] is a formidable task. In QR 9,[2] solutions were given for complex ω $(=\omega_r + j\omega_i)$ and real k. This is sufficient to indicate whether or not instabilities are to be expected, without defining whether they will be convective or absolute. The most significant results are for variation of beam radius. Although there is no interaction with the body wave if $(b/a) = 1$, even for $(b/a) = 1.01$ there is an indication that both body and surface wave interaction will be important in practice: two regions of complex ω are predicted. For $(b/a) = 1.10$ the maximum values of ω_i are approximately equal for the two unstable regions. Beyond this point, the beam/body wave interaction dominates. This is necessarily true only if the instability turns out to be absolute, although it would be expected that convective growth in the beam/surface wave mode would be weakest for a thin beam

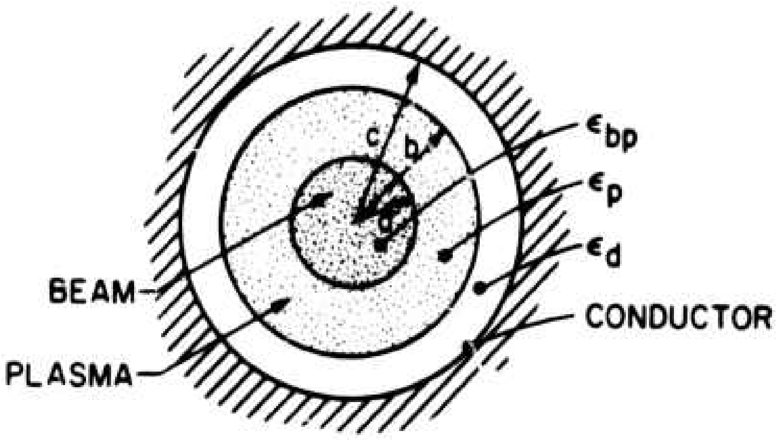


Fig. 1. GEOMETRY FOR BEAM/PLASMA AMPLIFICATION ANALYSIS.

During the reporting period, attention has been given to the full stability analysis of Eq. (1) with complex ω and complex k. It was decided to carry out the first calculations for the limiting case of the beam filling the plasma $(b/a = 1)$. This should provide the maximum growth in the surface wave modes, and the strongest fields outside the plasma region, i.e. it is the situation which should provide strongest coupling to an external circuit. A variety of difficulties have been encountered, mainly in connection with the large argument complex Bessel function evaluations required by the analysis. These have mostly been resolved now, and detailed computations will be presented in the next QR. The results will be compared with the experimental data presented in several previous QR's.

III. ELECTROSTATIC WAVE AMPLIFICATION IN MAGNETOPLASMAS

When the beam and/or plasma have directed or thermal motions in the directions transverse and axial to the magnetic field, it is necessary to derive the appropriate dispersion relations using a Boltzmann equation formalism. The results of doing so were discussed rather generally in QR 1 where it was pointed out that, for a high enough value of the parameter (ω_b/ω_c), i.e. the radio of beam plasma frequency to electron cyclotron frequency, even an ion-neutralized electron beam could be unstable, and that in the presence of a background plasma the instability threshold for the beam density could be reduced. The purpose of this project is to investigate such interactions, and to determine their potentialities for microwave applications.

Numerous theoretical predictions of the instabilities have been made at Stanford and elsewhere. Basically, the theory predicts growth in pass-bands centered on the electron cyclotron harmonic frequencies $(n\omega_c)$. No further computations will be carried out under this project until our experimental parameters have been measured. Those computations carried out to date have been summarized by Tataronis.[3]

So far, few controlled experiments have been carried out to check the theory, though observations of strong noise emissions from magneto-plasmas containing charged particles with appreciable transverse velocities provide significant support for the existence of the predicted mechanisms. The studies planned under this contract are intended to provide results under refined experimental conditions, and to put the theory on a firm quantitative basis. The aim is to excite growing waves by means of an electron beam injected into the plasma, and to study the variation of the growth rate as a function of the longitudinal and transverse energies of the beam. This immediately poses two experimental problems: production of the beam, and measurement of its parameters. Our work on these topics has been summarized in report form during the quarter,[4] and will be circulated shortly. Progress on the observation of instabilities is as follows.

(A) Observations of Emissions from the Plasma

Amongst computations carried out earlier under this contract are those shown in Fig. 2.[5] They show the instability threshold for a mixture of a Maxwellian distribution and a beam monoenergetic in both the axial and transverse directions, i.e. a "ring" distribution. Note that at low values of (ω_p^2/ω_c^2) the plasma is stable. Then, as (ω_p^2/ω_c^2) is increased at a constant value of α (= proportion of background plasma) the passbands become unstable progressively. If the ratio of beam velocity to thermal velocity of the background plasma (v_{01}/v_t), and α are large enough, a further increase in (ω_p^2/ω_c^2) will stabilize the plasma again, the lower harmonics being stabilized first. As a second example, consider the effect of moving on a diagonal from the lower left to the upper right on the diagrams of Fig. 2. Note that the plasma will become unstable and then stabilize again, the lower harmonics being stabilized first.

We believe that the occurrence of such phenomena has been confirmed by our results obtained during the reporting period. The first case just described is shown experimentally in Fig. 3. Here (ω_p^2/ω_c^2) was increased by increasing the beam current. Since the beam produces the background, it was assumed that α remained approximately constant. Qualitatively, the behavior of the radiation agrees with theory: radiation intensity first increasing and then decreasing with increasing (ω_p^2/ω_c^2).

The second example is shown experimentally in Fig. 4. The only parameter varied was the background pressure, which changes both α and (ω_p^2/ω_c^2). Again one can see qualitative agreement with theory: the lower harmonic radiation being quenched by increasing the background pressure.

Although the correlation between theory and experiment is good, it should be pointed out that our experimental set-up does not give exactly the ring distribution used in the theory. The beam has a spread of velocities. The original computer program is being modified to solve the dispersion relation for the case in which the beam has a finite spread. This work is nearly complete, and will enable us to make quantitative comparisons between the experimental velocity distribution and theory for the instability thresholds.

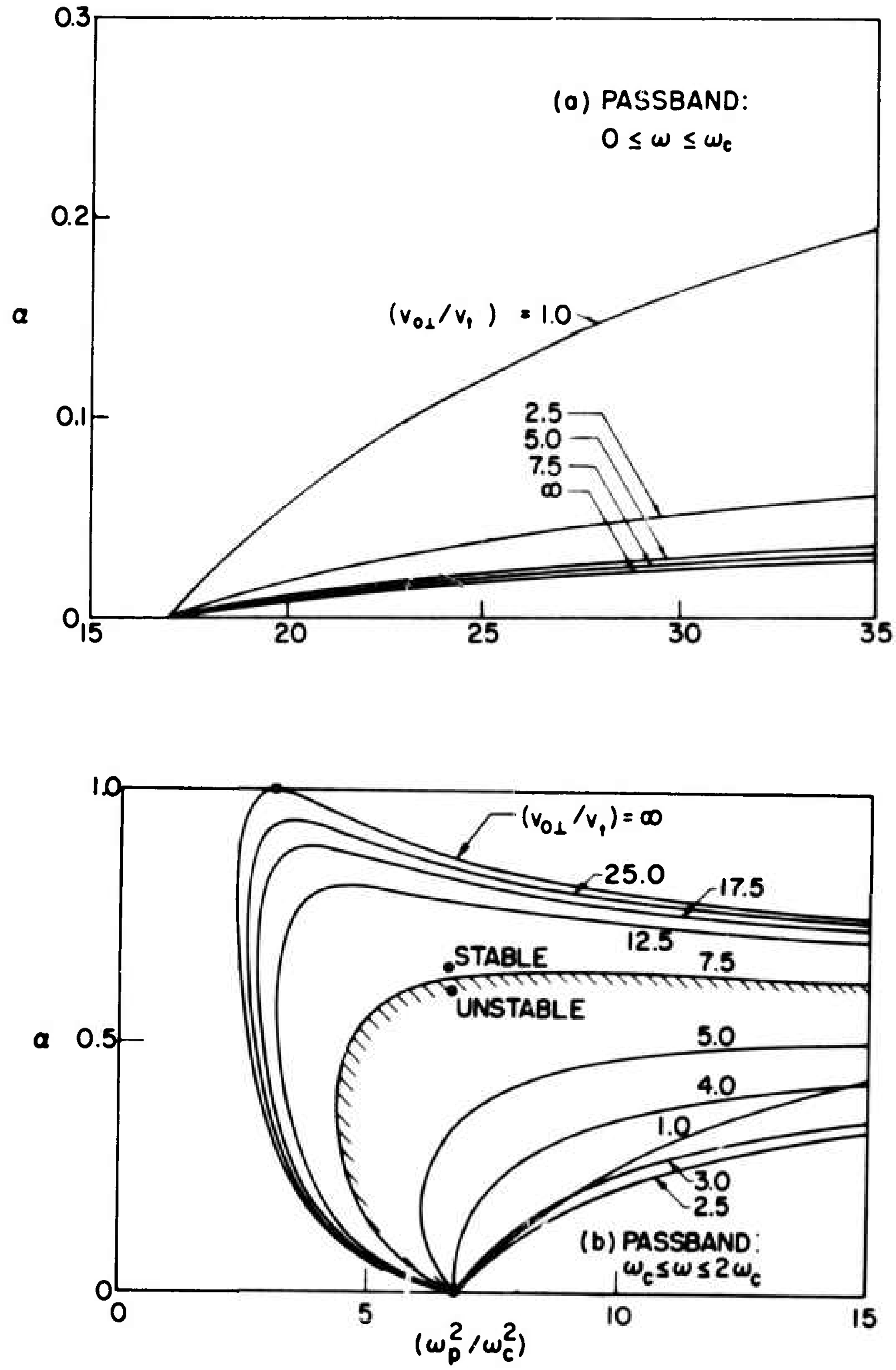
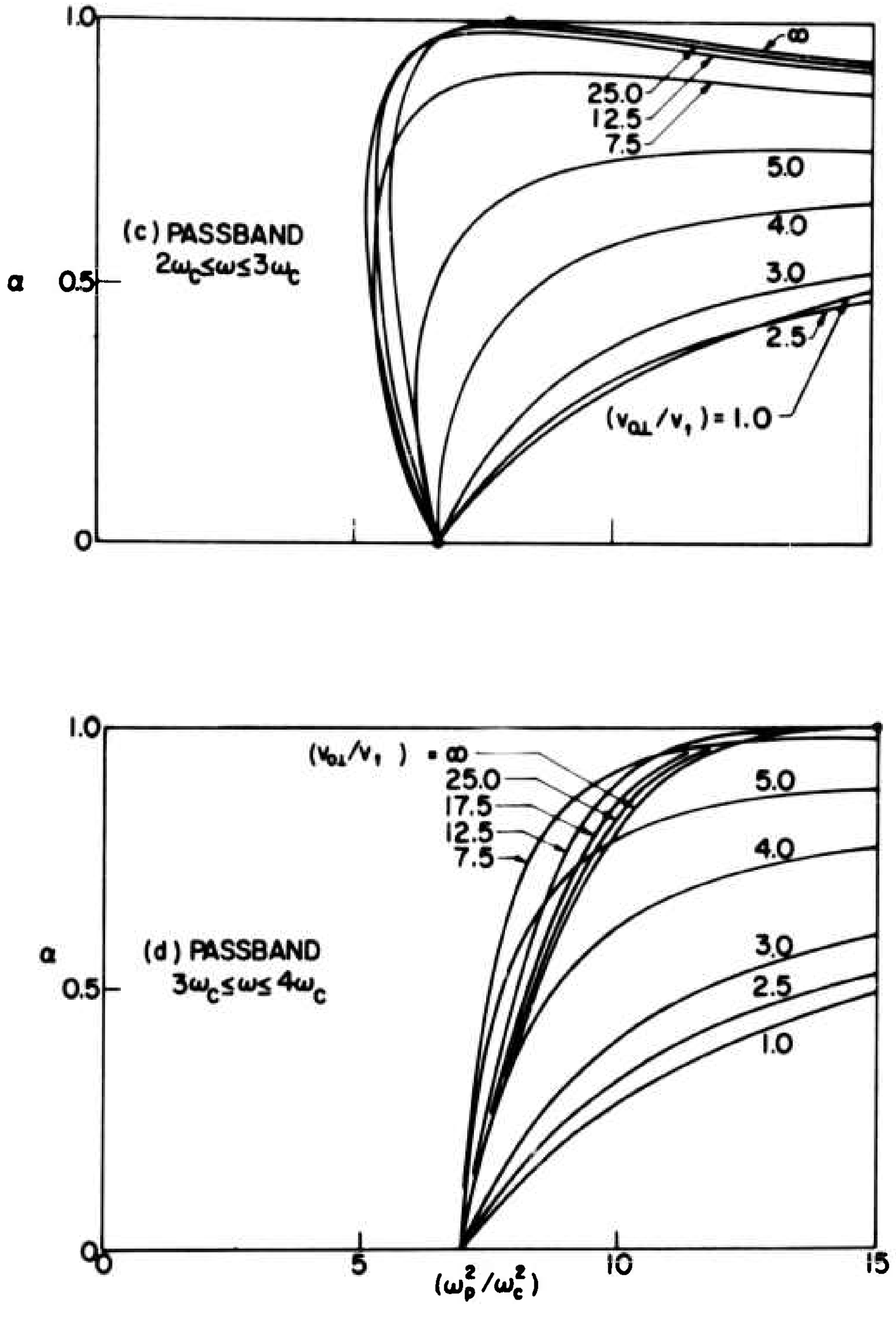


Fig. 2. CRITERIA FOR THE ONSET OF INSTABILITY FOR PERPENDICUARLY PROPAGATING CYCLOTRON HARMONIC WAVES IN A MIXTURE OF (α) MAXWELLIAN AND ($1-\alpha$) RING ELECTRON VELOCITY DISTRIBUTIONS.



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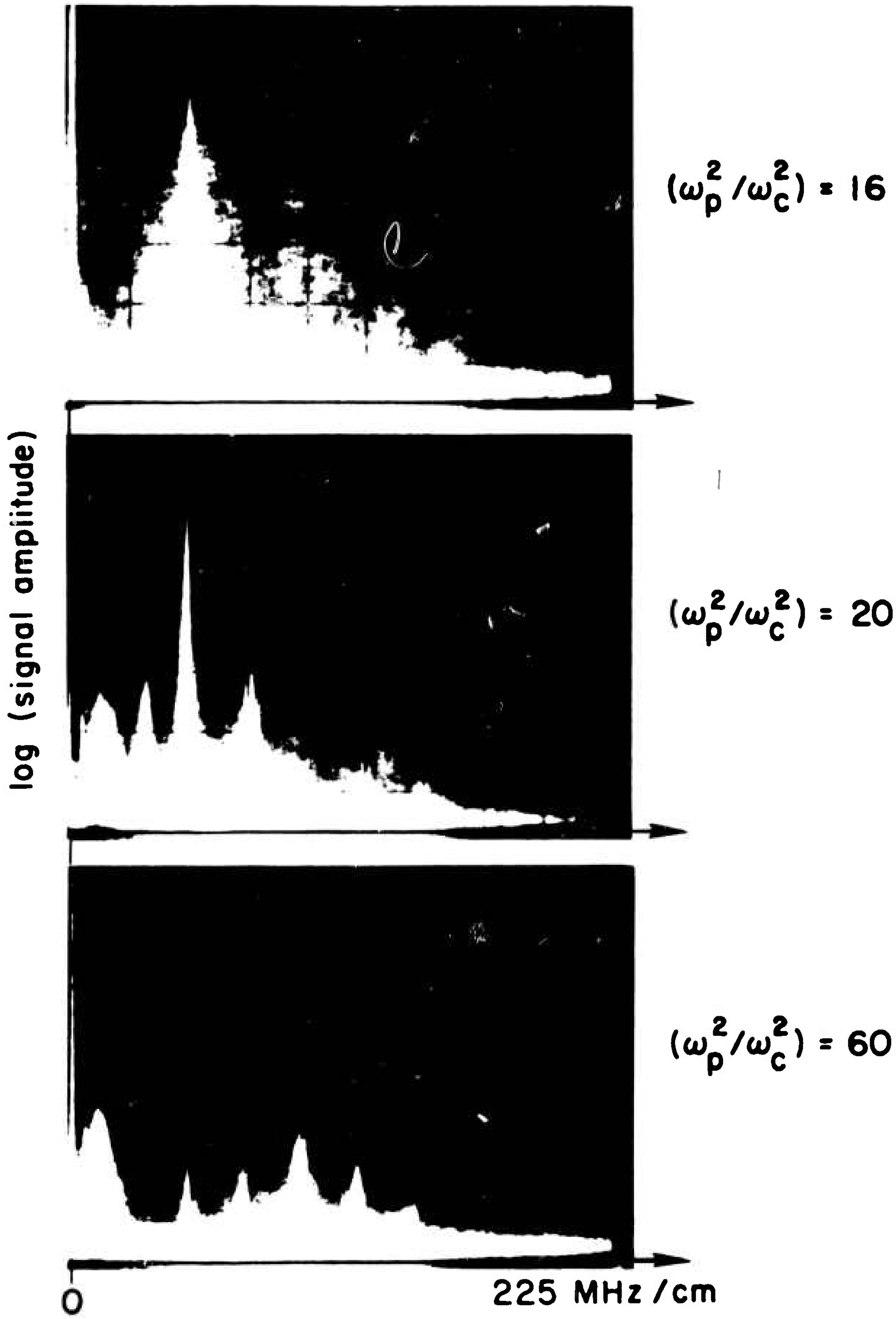

Fig. 5. NOISE EMISSION FROM A MAGNETOPLASMA DUE TO AN ELECTRON BEAM WITH TRANSVERSE ENERGY: EFFECT OF VARYING (ω_p^2/ω_c^2) [$\alpha \approx 0.99$, $f_c = 230$ MHz, $p = 6 \times 10^{-4}$ Torr, $V_b = 160$ V].

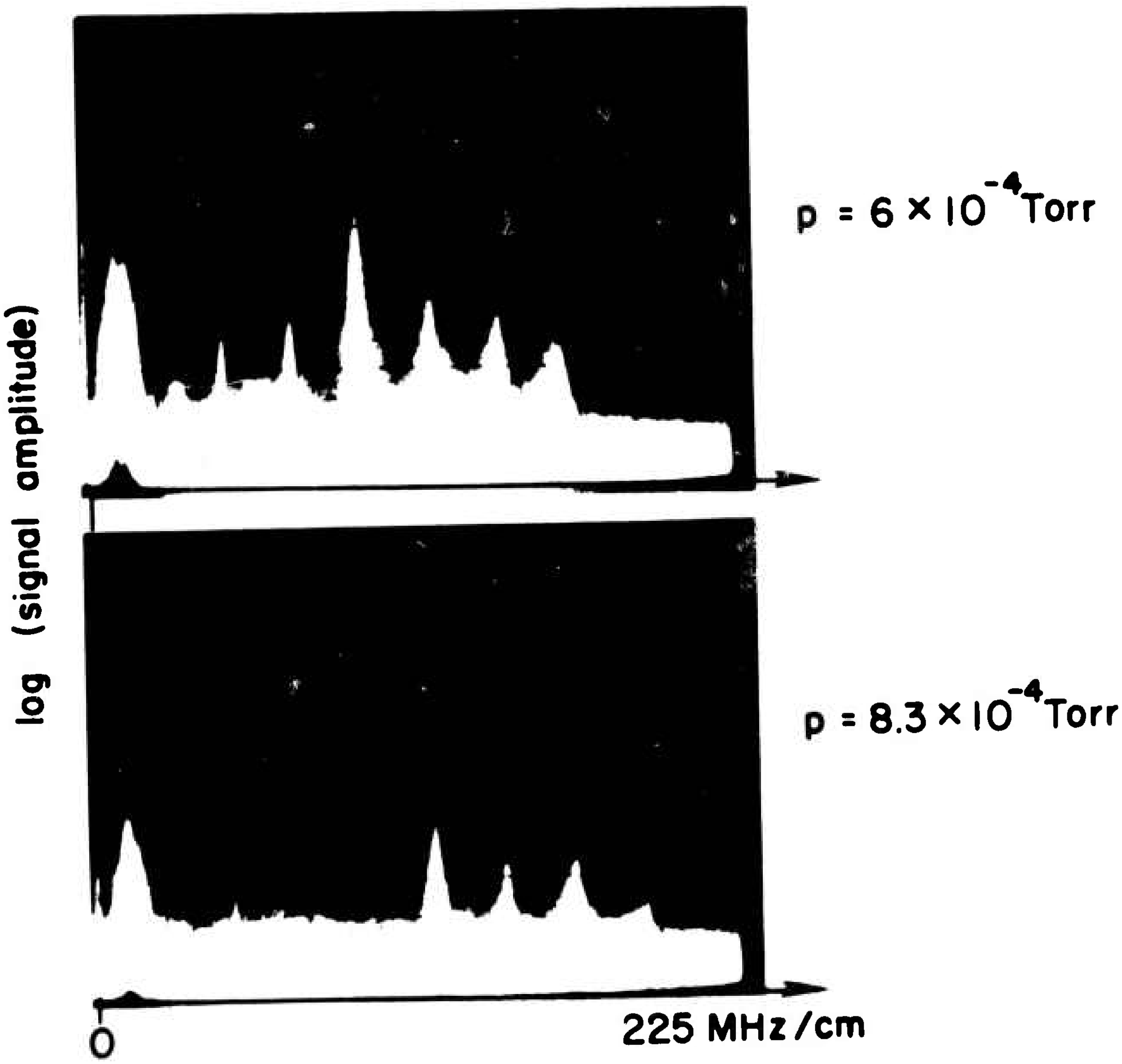

Fig. 4. NOISE EMISSION FROM A MAGNETOPLASMA DUE TO AN ELECTRON BEAM WITH TRANSVERSE ENERGY: EFFECT OF VARYING BACKGROUND PRESSURE [α = 0.990 - 0.995, f_c = 230 MHz, V_b = 160 V].

IV. ELECTROMAGNETIC WAVE AMPLIFICATION IN MAGNETOPLASMAS

In the absence of a static magnetic field, interaction of an electron beam with a plasma leads only to electrostatic beam/plasma interactions of the types described in Section II. When a static magnetic field is present, there are additional possibilities of electromagnetic wave interaction. That chosen for study under the present contract was the interaction with the right-hand polarized electromagnetic wave known in ionosphere terminology as the "whistler" mode. It has been demonstrated theoretically that under conditions where a beam with transverse energy interacts with the plasma, wave growth in this mode should be possible. This led immediately to the question of whether there are experimental situations in which this growth dominates over the electrostatic growth mechanisms occurring at the same time. After a comprehensive parameter study,[5] we have concluded that strong small-signal growth in electrostatic wave modes will preclude observation of whistler growth for laboratory plasma parameters likely to be of interest from the device point of view.

Two further developments of this project are now being pursued. The first is to explore other velocity distributions to determine whether conditions exist for which growth in the whistler mode predominates over other types of instabilities. There is some evidence, from observation of whistler amplification in the magnetosphere, that such conditions exist. The second is to examine mechanisms for whistler amplification in which the energy source to provide wave growth is not supplied in the form of an electron beam or other velocity-space anisotropy. Progress made on these topics during the reporting period is as follows.

(A) Loss-Cone Instabilities

The loss-cone velocity distribution occurs typically in mirror geometries, where particles with sufficient axial velocity can escape through the ends. The particular case of interest here is of a small population of high-energy electrons with a loss-cone distribution interacting with a cold background plasma. There are numerous observations in the laboratory of emission below the cyclotron frequency from such plasmas, and it seems

highly likely that whistler instability is being excited. Similar situations and phenomena occur in the magnetosphere.

During the quarter, work on the stability classification has begun. The theory leading to the dispersion relation involved is quite straightforward, and need not be quoted here. The stability analysis follows the usual method described by Briggs.[1] The main points of interest are to determine the nature of the instability, i.e. absolute or convective, and the corresponding growth rates. According to some recent work, the instability occurs typically near $(\omega_c/2)$,[6] and is convective.[7] If so, it should be possible to carry out controlled experiments on wave amplification. These questions will be pursued during the coming quarter.

(B) Parametric Amplification in the Whistler Mode

If the synchronism conditions,

$$\omega_p = \omega_s + \omega_i \quad , \qquad k_p = k_s + k_i \quad , \tag{3}$$

can be satisfied for three whistlers propagating parallel to the magnetic field, then the possibility exists of nonlinear interaction between a pump wave (p), a signal (s), and an idler (i). This, in turn, may lead to wave growth, i.e. parametric amplification. The question was studied in QR 9,[2] where it was shown that the coupling coefficients among the waves are identically zero. At first sight, this result may seem very surprising. Although the synchronism conditions can be satisfied, there is no wave/wave interaction and hence no possibility of parametric amplification. Physically, the explanation is to be found in the plane wave nature of the waves. The rf currents flow in the plane of the wave. There is consequently no rf space charge term to give rise to a current nonlinearity.

If the propagation were oblique to the magnetic field, these conditions would no longer be effective, and interaction should be obtained. This will be the case in experimental geometry where the plasma boundaries are important. During the reporting period, theoretical work has begun on the case in which only one of the three waves propagates parallel

to the magnetic field and the other two propagate obliquely. If the results look encouraging, the effects of boundaries will be included.

A direct check has been made experimentally to determine whether nonlinear coupling occurs in the bounded geometry of our laboratory system. Two small dipole antennas, aligned with the magnetic field line and 6 cm apart, were used as pumping and detection couplers. An oscillator with 200 mW minimum output was used to pump the system at 2 GHz, and growth of both signal and idler at 1 GHz was looked for. This degenerate case is of special interest for the whistler since the synchronism conditions are satisfied, independent of the plasma density, at $\omega_p = (2\omega_c/3)$ and $\omega_s = \omega_i = (\omega_c/3)$, for parallel propagation. It may be expected that growth will be observed near these conditions in the bounded case, or for oblique propagation.

Figure 5 shows typical results with the magnetic field adjusted to give a cyclotron frequency of 3.08 GHz. The bottom trace shows ion saturation current to a probe during the afterglow, a criterion for electron density. There is a peak in the afterglow which was found to be very sensitive to the plasma parameters, and the magnetic field strength. It may be remarked that a 1.5 GHz low-pass filter was inserted before the receiver to eliminate the possibility of nonlinear effects occurring in the receiver crystal itself. Further experiments will continue during the coming reporting period.

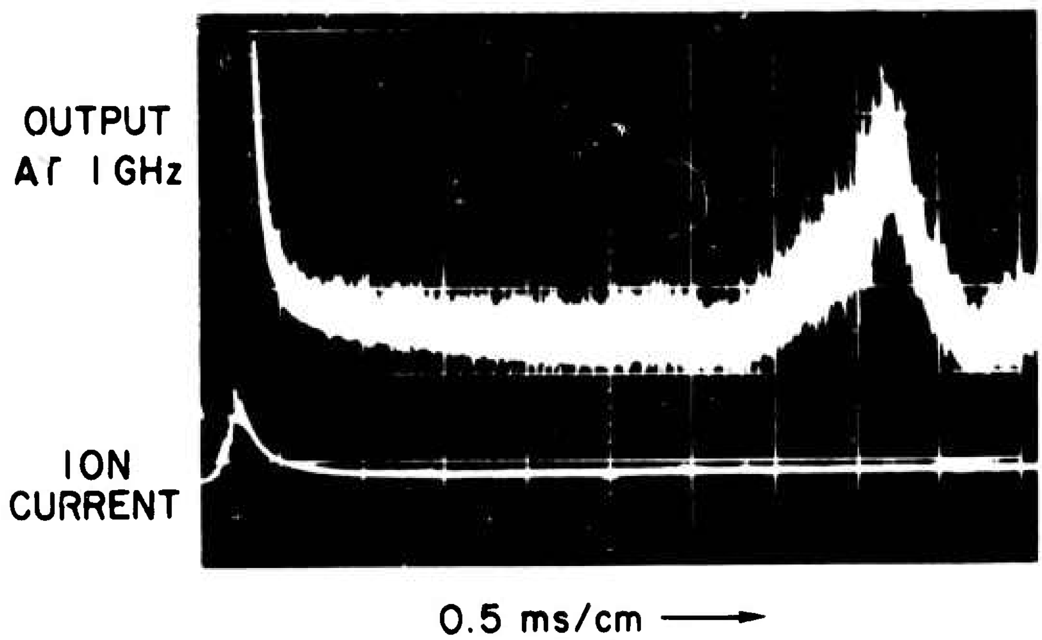

Fig. 5. DEGENERATE PARAMETRIC AMPLIFICATION IN THE WHISTLER MODE [$f_p = 2$ GHz, $f_s = f_i = 1$ GHz, $f_c = 3$ GHz].

V. FUTURE PROGRAM

Most of the details of our program for the coming quarter have been dealt with in the relevant theoretical and experimental subsections of Sections II-IV. Summarizing, the program is as follows:

(i) Beam/plasma amplification with transverse modulation. Theoretical work will continue on beam/surface wave interactions in the $m = 0$ and $m = 1$ modes, with particular emphasis on the nature of the wave growth, i.e. absolute or convective.

(ii) Electrostatic wave amplification in magnetoplasmas. Further measurements of the noise spectrum due to magnetoplasma wave excitation by electrons with transverse energy will be made, first with a view to identifying the various frequencies so far observed, then with the aim of further verifying the theory quantitatively for a delta-function beam interacting with a warm plasma. Attempts will be made to derive tractable analytic expressions for the instability boundaries in parameter space.

(iii) Electromagnetic wave amplifiers in magnetoplasmas. Instabilities of the loss-cone type will continue to be investigated, particularly with regard to instability classification, and competing modes. Theory and experiment on parametric amplification in the whistler mode will be extended.

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1. Crawford, F. W., "Experimental Verifications of Microscopic Plasma Theory"
   *International Symposium on Single-Particle Distributions Functions, Marburg, Germany, August 1968.
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13. ABSTRACT

This report describes a program of work in which both electrostatic and electromagnetic wave amplifying mechanisms are under investigation. For the former, studies in the absence of a static magnetic field are directed towards verifying the theory for beam/surface wave amplification. Two distinctly different lines are being followed for interactions in the presence of a static magnetic field: Electrostatic cyclotron harmonic wave interaction is being examined, both theoretically and experimentally, and the potentialities of electromagnetic wave growth in the "whistler" mode are being investigated.

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Transverse Interaction						
Microwave Amplification						
High Power						
Parametric Amplification						
Whistlers						